Study of Nonlinear Corrections to the KamLAND Energy Scale

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KamLAND [1] is a large liquid scintillator calorimeter. Low and medium energy alpha, beta, and gamma particles that are produced by calibration sources, by the decay of radioactive contaminants, or by neutrino interactions in the fiducial volume will deposit its full ("real") energy into the KamLAND detector with a high probability. A small fraction of this "real" energy will be converted into optical photons by the scintillator and a few percent of these scintillation photons will be detected by the KamLAND photomultiplier tubes (PMT). The KamLAND analysis uses several algorithms to compute a quantity called "visible" energy from the integrated current (charge) on the PMT anodes. To first order, this "visible" energy is essentially the number of detected scintillation photons (photoelectrons) with some spatial and dark noise corrections. Ideally, the "real" energy will be proportional to the "visible" energy for all particle types and energies. In reality, there are at least two known effects that will destroy this linear relationship. The first effect is quenching where the production of scintillation photons saturates for highly ionizing particles. The second effect is the production of optical Ĉerenkov photons which depends on the particle velocity.

We have calculated the "visible" energy ($\mathrm{E_{vis}}$) to "real" energy (E) correction for the KamLAND detector where the correction function, f(E), is assumed to take the form: $\mathrm{f(E)} \equiv \frac{\mathrm{E_{vis}}}{\mathrm{E}} = 1 - \delta_{\mathrm{q}}(\mathrm{E}) + \mathrm{k}_0\delta_0(\mathrm{E}) + \mathrm{k}_{\hat{c}}\delta_{\hat{c}}(\mathrm{E})$ where $\delta_{\mathrm{q}}(\mathrm{E})$, $\delta_0(\mathrm{E})$, and $\delta_{\hat{c}}(\mathrm{E})$ are energy and particle dependent parameters that come from a Monte Carlo calculation and k_0 and $\mathrm{k}_{\hat{c}}$ are energy and particle independent parameters that are determined by a fit to calibration data. The parameter $\delta_{\mathrm{q}}(\mathrm{E})$ is the fractional "visible" energy loss due to the quenching of scintillation light and is calculated according to Birks' Law [2] where Birks' constant is determined from the alpha decays of ^{214}Po and ^{212}Po which are radon daughters. The parameter $\delta_0(\mathrm{E})$ is also a quenching correction, but it is for the amount of "visible" energy "lost" in the Monte Carlo calculation due to the finite particle tracking threshold. The coefficient k_0 allows for some of this sub-threshold energy to be recovered. The term $\mathrm{k}_{\hat{c}}\delta_{\hat{c}}(\mathrm{E})$ represents the Ĉerenkov contribution to the "visible" energy. The EGSnrc [3] Monte Carlo package was used to calculate $\delta_{\mathrm{q}}(\mathrm{E})$, $\delta_0(\mathrm{E})$, and $\delta_{\hat{c}}(\mathrm{E})$ for γ-rays, e^-, and e^+ in the KamLAND scintillator. The energy and particle independent model parameters k_0 and $\mathrm{k}_{\hat{c}}$ were determined by performing a fit to the KamLAND calibration data. Fig. 1 shows the correction curve for γ's with "real" energy up to 8 MeV and shows very good agreement with the measured calibration data.

FIG. 1: The γ-ray "visible" energy to "real" energy correction function (solid line). The gray region represents the $\pm1\sigma$ systematic uncertainty of the model. The points are the measured "visible" energy to "real" energy ratios from the calibration data: ^{68}Ge (2×0.511 MeV), ^{65}Zn (1.116 MeV), ^{60}Co (1.173 MeV + 1.332 MeV), $^{1}\mathrm{H}(\mathrm{n},\gamma)^{2}\mathrm{H}$ (2.225 MeV), $^{12}\mathrm{C}(\mathrm{n},\gamma)^{13}\mathrm{C}$ (4.946 MeV), and moderated AmBe ($^{9}\mathrm{Be}(\alpha,\mathrm{n})^{12}\mathrm{C}^*$, 7.654 MeV). The data points corresponding to calibration sources with two γ-rays are plotted with half the true "real" energy.

[1] K. Eguchi, *et al.,* Phys. Rev. Lett. **90**, 021802, (2003).
[2] J. B. Birks, *The Theory and Practice of Scintillation Counting*, (Pergamon, London, 1964).
[3] I. Kawrakow and D. W. O. Rogers, *The EGSnrc Code System: Monte Carlo Simulation of Electron and Photon Transport*, unpublished.